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THE NEXUS BETWEEN SOLAR ACTIVITY AND POPULATION DISPLACEMENT: THE CASE STUDY OF SOUTHERN EUROPE

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Abstract: Solar activity, as the dominant feature of the Sun, has an impact on nature, technology, humans, and their activities on Earth. The aim of this paper is to investigate the linkages between solar activity, natural disasters, and population displacement in Southern Europe, particularly focusing on the characteristics of natural disasters induced displacement during different phases of solar activity. For the purpose of the paper, data on solar activity and displacements induced by hazards category and type in the period 2008–2023 (24 and 25 Solar Cycle) were collected. The quantitative analysis is supported by statistical procedures (seasonal-trend decomposition by Loess—STL, tests for stationarity, correlation analysis, cross-correlation functions—CCF, vector autoregression—VAR, linear regression model, principal component analysis—PCA, k-means) computed in the software R. The results show certain linkages between solar activity and displacements induced by weather related hazards, and indicate that the intensity of this type of displacement is significantly higher during periods of greater solar activity. This paper opens up new horizons for future research in the field of solar activity impact on population displacement.

Keywords: solar activity; population displacement; natural disasters; Southern Europe

1. Introduction

The Sun is the center of our Solar System and the main source of energy for the Earth and other planets in the Solar System (Tentomas & Marsellos, 2022; Tsuda et al., 2015). As a dominant feature of the Sun, solar activity is characterized by the rise and fall of the number and area of sunspots during the 11-year cycle (Balogh et al., 2014; Hathaway, 2010). The part of the cycle with low sunspot activity is called solar minimum, while the opposite is solar maximum (Singh & Patel, 2021). Comprehending the variations of the solar cycle is important due to its influence on Earth (Hathaway, 2015; Whitehouse, 2020). As the Sun plays a role in shaping weather and climate (Xiao et al., 2024), unpredictable processes, such as natural disasters, can be related to the extreme solar radiation (Nina et al., 2019; Srećković, 2023; Srećković et al., 2025). Natural disasters, at the same time, are recognized as

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an increasingly important factor of population mobility and displacement worldwide (Langović et al., 2024; Marchiori et al., 2012; Mbaye & Okara, 2023; Sida, 2024).

The aim of this paper is to examine the relationship between solar activity, natural disasters, and population displacement in Southern Europe. The research attempts to determine whether there are differences in patterns of displacement induced by natural disasters during different periods of solar activity. The ultimate goal of the research is to contribute to understandings of the Sun-Earth system. As research into the relationship between solar activity and population displacements, according to the authors' knowledge, has not yet been addressed in the literature, this paper makes a contribution to the consideration of future research questions in this area.

2. Background of the research

2.1. Solar activity and natural disasters

Numerous studies have investigated the effects of solar activity on natural disasters and point to different patterns in the relationships between these categories (Malinović-Milićević et al., 2023; Malinović-Milićević et al., 2024; Milenković et al., 2011). Accordingly, there is evidence that the intensity of certain natural disasters is related to the most prominent years of solar activity, and can therefore increase during periods of low solar activity, during solar maximum, or both.

One of the research established that in Central Europe, flood frequency is higher when solar activity is reduced (Czymzik et al., 2016). By comparing sunspot data with monthly precipitation series of 39 European countries, Laurenz et al. (2019) found that flood frequency usually increases during times of low solar activity due to the existence of a time lag between these processes. Hong-yan et al. (2015), on the example of the Second Songhua River Basin, showed that flood years mainly appear in solar maximum year, years after solar maximum year and solar minimum year. Dmitrieva et al. (1998) indicated that the maximum occurrence of droughts in Europe and Russia coincides with the sunspot maximum or is observed during the growth phase of solar activity.

Yanchukovsky (2021) established that an increase in the number of strong earthquakes on the planet occurs during the decline phase of solar activity and during solar minimum. Shestopalov and Kharin (2014) determined a significant negative correlation between seismicity and solar activity. The research results by Gomez and Radovanović (2008) regarding the ignition of forest fires and solar activity indicated that there is a strong causality relationship between them in South-Western Europe. In addition, Radovanović et al. (2015) found a certain correlation between solar activity and fires in Southern Europe.

2.2. Natural disasters and population displacement

Natural disasters have a significant role in forcing people to flee their homes (UNFPA, 2024). The relationship between natural disasters and mobility is often described as one of the greatest challenges of our time and future sustainable development (EMN, 2023; Mbaye & Zimmermann, 2015).

Floods, earthquakes, storms, volcanic activity, droughts, and other natural disasters influence millions of displacement every year (South American Conference on Migration, 2022). According to data from the Internal Displacement Monitoring Centre (IDMC, 2025), in

2023 the total number of internal displacements globally was 26.8 million. Floods (9.7 million), storms (9.5 million), and earthquakes (6.4 million) had the greatest impact on internal displacement. There is a presumption that displacement due to climate change will intensify in the coming decades and accelerate even further after 2050 (Stojanov, 2021).

Marchiori et al. (2012) found that weather anomalies, i.e. temperature and rainfall anomalies increased population mobility. Another study indicated that coastal communities are particularly vulnerable to floods due to the increase in extreme rainfall and storm surges associated (Ekoh et al., 2022). Examining the impact of earthquakes on mobility patterns in New Zealand, Fabling et al. (2022) found that significant emigration occurred following the second (more severe) earthquake. McConnell et al. (2021) found significant migration probability among tracts that experienced the most destructive wildfires in the USA. In addition, McConnell et al. (2024) in another research in the USA confirmed that only the most extreme wildfires influenced migration and that the others (majority) did not cause significant changes in migration patterns.

3. Methodology

3.1. Data

The methodological framework of the research is based on datasets on Solar cycle 24 and Solar cycle 25 (current cycle) and internal displacement induced by natural disasters (note: in this paper also “displacement” or “population displacement”) for the period 2008–2023.

For the purposes of this paper, a wide range of solar indicators were considered. The research included annual data on sunspot number, C-flares, M-flares, X-flares, as well as monthly data on monthly mean sunspot number, monthly smoothed sunspot number, observed radio flux, and smoothed radio flux retrieved from SpaceWeatherLive.com (https://www.spaceweatherlive.com/en.html).

The research included annual and monthly data on internal displacement collected by the IDMC (https://www.internal-displacement.org/). The IDMC organizes the data according to the hazards that have led to internal displacement. In this context, the data on displacement by hazard category have been included and divided into two groups:

- Internal displacement induced by weather-related hazards and
- Internal displacement induced by geophysical hazards. Each of these groups takes into account different types of hazards that lead to internal displacement. According to the IDMC, an internal displacement refers to “each new forced movement of a person within the borders of the country of their habitual residence recorded during the year” (IDMC, 2023, p. 3).

In order to make the text, figures, and tables clearer, the following abbreviations were used: Total internal displacements (In total ID), Internal displacements induced by weather related hazards (Weather related ID), Internal displacements induced by geophysical hazards (Geophysical ID).

3.2. Procedures and clarifications

To prepare the dataset for multivariate statistical analysis, all numeric variables were standardized to ensure comparability, and missing values were handled through listwise deletion (Little & Rubin, 2002). These preprocessing steps ensured the integrity of subsequent correlation, principal component, and clustering procedures.

The analytical framework was implemented sequentially to support transparency and reproducibility. First, the temporal dynamics of internal displacements were analyzed using seasonal-trend decomposition by Loess (STL), isolating trend, seasonal, and irregular components (Cleveland et al., 1990). Tests for stationarity were then applied to assess the suitability of the data for time-series modeling, including the ADF, KPSS, and Phillips–Perron tests (Kwiatkowski et al., 1992). Correlation and partial-correlation analyses were conducted to explore linear associations between solar activity indicators and displacement patterns (Shumway & Stoffer, 2017).

To explore causality, a vector autoregression (VAR) model was fitted, with lag length selected using standard information criteria (AIC, BIC, HQ) to balance goodness-of-fit and parsimony (Lütkepohl, 2005). Granger causality tests were subsequently performed to identify potential temporal dependencies between solar variables and internal displacements (Granger, 1969; Lütkepohl, 2005).

Principal Component Analysis (PCA) was applied for dimensionality reduction, allowing for the identification of latent patterns in the data (Jolliffe, 2002). This was followed by k-means clustering to detect underlying group structures, with the silhouette method used to determine the optimal number of clusters (Rousseeuw, 1987). In parallel, a linear regression model was estimated to assess direct linear relationships between solar indicators and displacement categories; given its limited explanatory power, this research relied more on flexible multivariate techniques (Montgomery et al., 2021).

Although autoregressive models such as ARIMA are commonly applied in univariate time-series forecasting, they were not employed here. The main objective was not to predict a single series, but to explore temporal dependencies between pairs of series. For this reason, the focus was on cross-correlation functions (CCF) to identify potential lead-lag relationships (Box et al., 2015; Shumway & Stoffer, 2017). In contrast, ACF/PACF was primarily used for ARIMA identification and treated as supporting diagnostics (Box et al., 2015). All analyses were conducted in *R* with reproducible scripts and fixed random seeds (R Core Team, 2024).

3.3. Study area

The study area covers the territory of Southern Europe. Given that the IDMC data refer to internal displacements that take place within one country, for the purposes of this paper, these data are considered at the level of one region – Southern Europe, and particularly refer to the following countries: Serbia, North Macedonia, Montenegro, Croatia, Bosnia and Herzegovina, Slovenia, Greece, Bulgaria, Albania, Italy, Spain, and Portugal. The IDMC (2024) did not record data on internal displacements in the microstates in this area (Vatican City, San Marino, Monaco, Andorra, and Malta) in the observed period.

This region is exposed to a number of natural disasters. In the period 2008–2023, around 300 natural disasters occurred in this area. Floods were the most frequent natural disasters, followed by extreme temperatures and storms (EM-DAT, 2025).

According to the IDMC (2024), more than 830,000 displacements were registered in the period 2008–2023 in Southern Europe. Weather related hazards influenced more displacement than geophysical hazards. As part of internal displacements induced by weather related hazards in Southern Europe, floods, wildfires, storms, mass movements, and extreme temperatures were particularly emphasized, while as part of internal displacements induced by geophysical hazards, earthquakes, mass movements, and volcanic activity were included. In terms of the hazard type, most internal displacements were induced by wildfire (36.5%), earthquakes (27.4%), floods (26.5%), and storms (8.5%) (Figure 1B). The highest volume of displacements was recorded in 2023 and 2014 (Figure 1A). In 2014, flood, which particularly occurred in Balkan countries (Serbia, Bosnia and Herzegovina, and Croatia), influenced intensive movements. In 2023, wildfires, predominantly in the Mediterranean countries (Greece, Spain, Italy, and Portugal) influenced most displacements. Storms that occurred in various parts of Southern Europe were also responsible for intensive displacements in 2023 (IDMC, 2024).

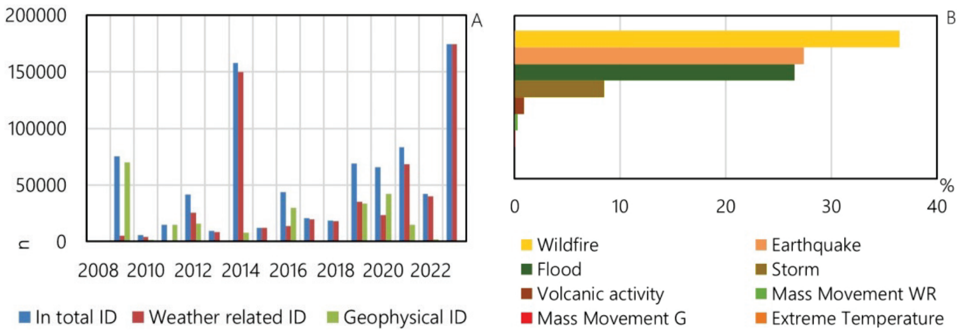

Figure 1. Population displacement in Southern Europe, 2008–2023:
Panel A: Internal displacements by hazard category (annually).
Panel B: Total Internal displacements by hazard type.
Note. Mass Movement G refers to the Mass movement related to the geophysical hazards and Mass Movement WR refers to the Mass Movement related to the weather related hazards.
Source. Authors' own calculations based on IDMC (2024).

4. Results

The comparative analysis between solar activity indicators (sunspot number, C-flares, M-flares, and X-flares) and the annual dynamics of internal displacements by hazard categories reveals patterns of temporal association. It was found that the highest intensity of internal displacements in Southern Europe in the period 2008–2023 was observed mainly during the years of the greatest solar activity. Accordingly, in the focus are the years 2014 and 2023. During Solar cycle 24, the largest number of internal displacements was recorded precisely during the phase of solar maximum in 2014. At the same time, overlaps in the 2023 are related to the beginning of the solar maximum phase in Solar cycle 25. Although no clear linkages could be established between the observed categories in the context of solar minimum, during these phases, the intensity of internal displacements is significantly lower than during the period of greater solar activity. The weather related ID shows similar pattern. At the same time, the Geophysical ID is characterized by a much more uniform feature and differs from the previously mentioned trends (Figure 2; Table 1). A comparative analysis at the monthly level between the solar activity indicators (monthly mean sunspot number and monthly smoothed sunspot number; observed radio flux and smoothed radio flux) and displacements confirms previous observations (Figures 2C and 2D).

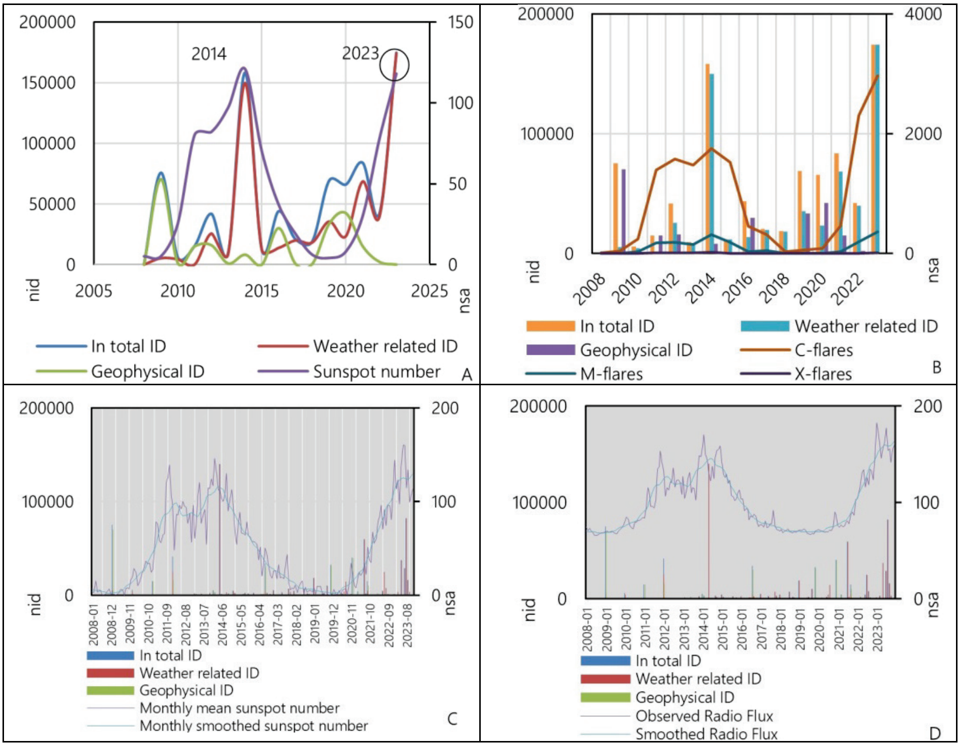

Figure 2. Solar activity and population displacement data:
Panel A: Annual data on sunspot number and internal displacements by hazard category, 2008–2023. Panel B: Annual data on C-flares, M-flares, and X-flares and annual data on internal displacements by hazard category, 2008–2023. Panel C: Monthly mean and smoothed sunspot number and monthly data on internal displacements by hazard category, 2008–2023. Panel D: Observed Radio Flux and Smoothed Radio Flux and monthly data on internal displacements by hazard category, 2008–2023.
Note. Nid refers to the number of displacements; nsa refers to the number of solar activity indicators.
Source. Authors' own calculation based on IDMC (2024) and SWL (2025).

Table 1. Maximum and minimum values of solar activity indicators and internal displacements, 2008–2023.

Categories	Max. (years)	Min. (years)
Internal displacement		
In total ID	2023/14	2008/10
Weather related ID	2023/14	2011/08
Geophysical ID	2009/20	2008/15
Solar activity indicators		
Sunspot number	2014/23	2019/08/09
C-flares	2023/22	2008/18
M-flares	2023/14	2008/18
X-flares	2014/23/13	2008/09/18/19/20

Source. Authors' calculations using data from IDMC (2024) and SWL (2025).

The analysis of the decomposition of the time series shows a clearly pronounced seasonality in the domain of weather related ID, which indicates a connection with the seasons and weather conditions. The winter months could be associated with severe storms, cold waves, and snow, while the summer months could be frequent with heat waves and wildfires. Additionally, a decreasing trend was observed in the period 2015–2020 (Figure 3A). The observation based on qualitative analysis suggests potentially reflecting improvements in prevention measures, reporting practices, or reduced event frequency. However, the result should be interpreted cautiously given possible confounding factors. Regarding the geophysical ID, no seasonal patterns were observed. The events are irregular and random, which is consistent with the nature of geophysical phenomena (Figure 3B).

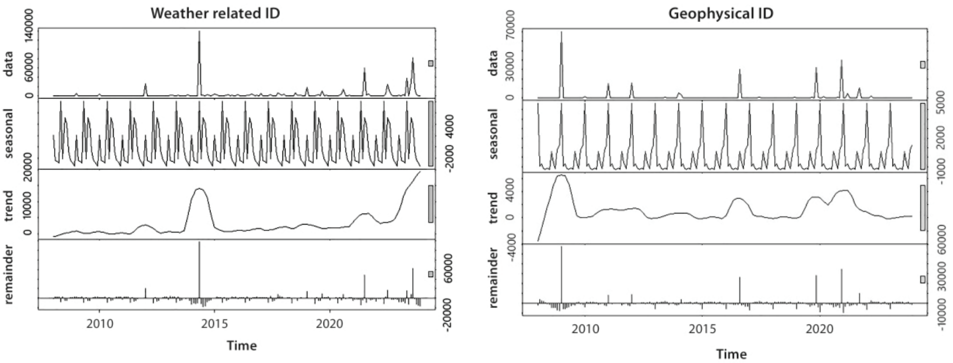

Figure 3. STL Decomposition of Time Series for Weather and Geophysical Internal Displacement: Panel A: Weather ID. Panel B: Geophysical ID.

Figure 4 contrasts the temporal behavior of displacement indicators with solar activity proxies. Geophysical ID exhibits rare, abrupt spikes without any discernible periodicity, confirming its essentially stochastic nature. In contrast, radio-flux indicators trace a smooth, quasi-11-year solar cycle, and sunspot counts follow the same broad curve with slightly higher short-term variability. Weather related ID shows intermittent peaks—most prominently in 2014 and 2023—that occur during phases of elevated solar activity, suggesting at least partial synchrony with the solar cycle. These patterns support the interpretation that geophysical ID arise from local, unpredictable drivers, whereas weather related ID may be modulated by solar variability. Granger-causality testing corroborates this: sunspots → weather related ID is significant (p = .022), whereas radio flux → geophysical ID is not (p = .89).

The results of the correlation matrix also indicate significant differences between weather related ID and geophysical ID and their relationship with solar indicators. Namely, a positive statistically significant correlation was found between solar indicators and weather related ID (Monthly mean sunspot number: r = .19, p = .001; monthly smoothed sunspot number: r = .20, p = .001; Observed Radio Flux: r = 017; p = .02; Smoothed Radio Flux: r = .21; p = .00). On the other hand, no statistically significant correlation was found between geophysical ID and solar activity indicators. From the perspective of the population displacements caused by the type of hazard, a positive statistically significant correlation was found between displacements caused by the storm and the solar indicators (monthly mean sunspot number: r = .21; p = .00; monthly smoothed sunspot number: r = .21; p = .00; observed radio flux: r = .21; p = .00; smoothed radio flux: r = .23; p = .00) and internal displacements caused by the movement of mass G and some of the solar activity indicators (monthly smoothed sunspot number: r = .17; p = .02; observed radio flux: r = .16; p = .02;

smoothed radio flux: r = .19; p = .01; Figure 5). This result suggests that in future research, particular natural disasters have the potential to be investigated in migration studies.

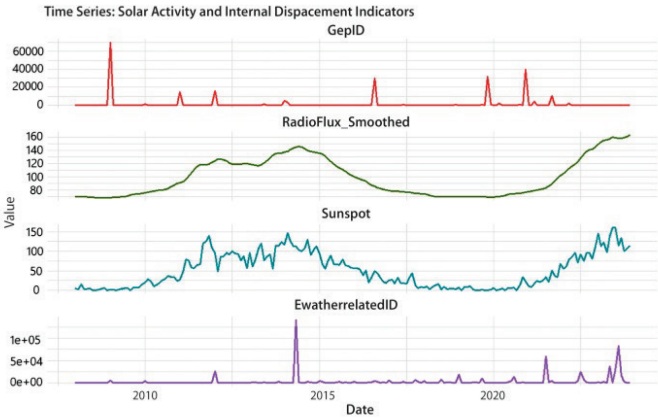

Figure 4. Behavior of displacement indicators with solar-activity.

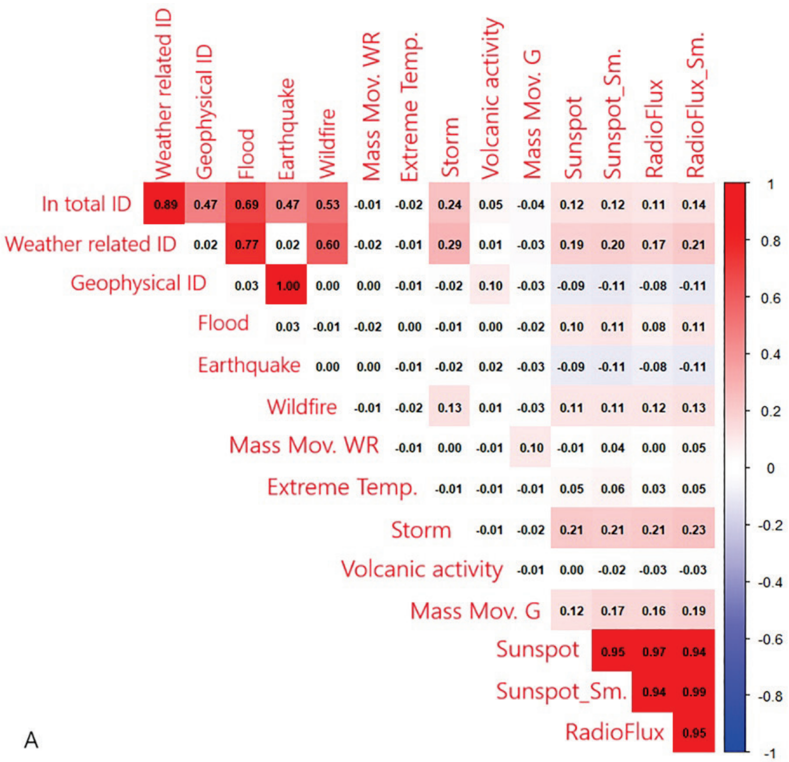

Figure 5. Correlation coefficients for solar indicators and population displacement: Panel A: The upper triangle correlation values graph.

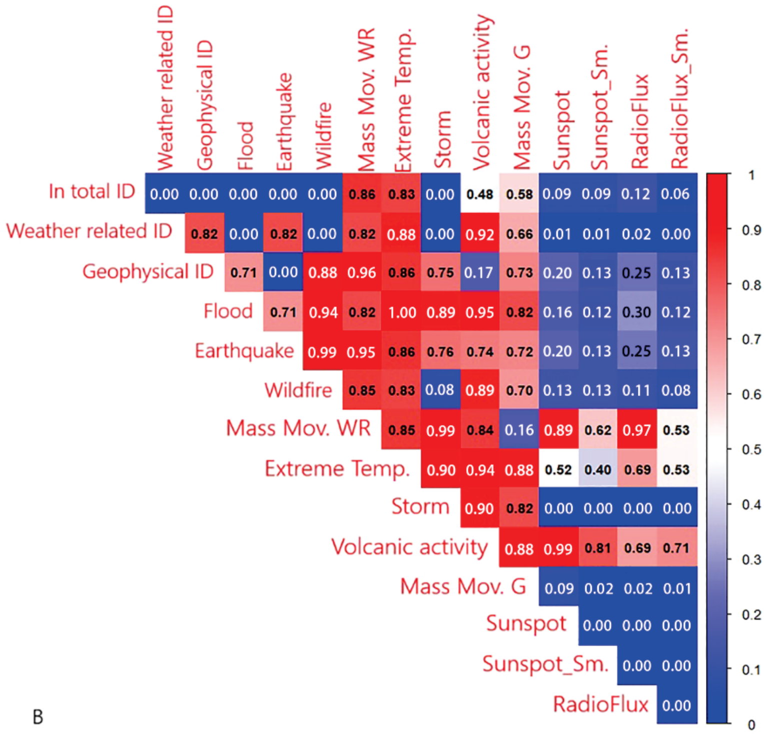

Figure 5. Correlation coefficients for solar indicators and population displacement:
Panel B: *P*-values of statistical significance of Pearson correlation (*r*) upper triangle graph.
Note. The *P*-values less than .05 are considered statistically significant.

The CCF was applied to evaluate the potential lagged relationship between sunspots and weather related ID. The plot (Figure 6) shows that sunspot activity leads to weather related ID by approximately 2–3 months, as evidenced by significant spikes at lags -2 and -3. This supports a plausible physical linkage whereby increased solar activity influences atmospheric conditions that later culminate in displacing events such as storms, wildfires, or floods.

In the context of weather related ID, all solar indicators proved to be statistically significant predictors, although with different signs of the coefficients. The regression model explains about 8.5% of the variance (R-squared ≈ .085). The positive effect of the number of sunspots and smoothed radio flux suggests that the increase in solar activity has a moderate but significant effect on weather related ID. On the other side, a negative coefficient for the observed radio flux may indicate a contradictory effect in the short term. Regarding geophysical ID, no predictor is statistically significant. The model has a very low R-squared (~ .017), which confirms that these events do not depend on solar activity indicators (Table 2).

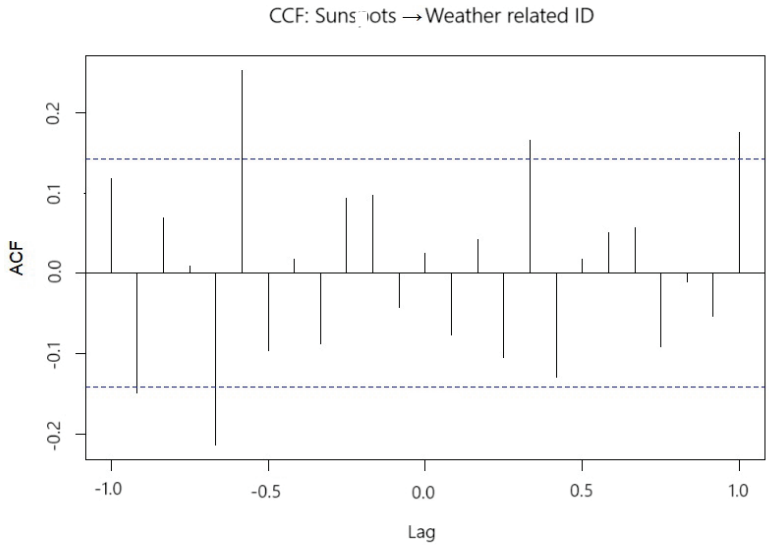

Figure 6. CCF between sunspots and weather related ID.
Note. The lag is expressed n discreite integer time units (months). Negative lag values indicate that variations in sunspot activity precede weather related displacements, while positive lag values imply the opposite relationship. Dashed lines represent the 95% confidence interval for statistical significance.

Table 2. Regression model for weather related ID and geophysical ID

Regression model for weather related ID					
Predictor	Coefficient	Std. error	*t*-value	*p*-value	95% CI
const	-26279.176	14171.469	-1.854	.065	[-54235.673, 1677.322]
Monthly_mean_sunspot	232.937	110.363	2.111	.036	[15.221, 450.653]
Monthly_smoothed_sunspot	-452.261	194.152	-2.329	.021	[-835.271, -69.251]
Observed_Radio_Flux	-415.015	161.465	-2.57	.011	[-733.541, -96.489]
Smoothed_Radio_Flux	821.586	278.89	2.946	.004	[271.41, 1371.762]
const	3034.113	7588.6	.4	.69	[-11936.153, 18004.379]
Monthly_mean_sunspot	-20.041	59.098	-0.339	.735	[-136.624, 96.543]
Monthly_smoothed_sunspot	11.07	103.965	.106	.915	[-194.026, 216.166]
Observed_Radio_Flux	71.986	86.462	.833	.406	[-98.58, 242.551]
Smoothed_Radio_Flux	-85.599	149.341	-0.573	.567	[-380.209, 209.012]

The dimensionality reduction performed using PCA reveals that the first two components (PC1 and PC2) explain over 80% of the total variance (65.6% + 16.9%, as shown in the Scree Plot; Figure 7A), thereby justifying a biplot-based interpretation. The PCA biplot (Figure 7B) indicates that variables related to solar activity (sunspot numbers and radio flux indicators) and the weather related ID exhibit strong alignment along PC1. This suggests a shared underlying dynamics, potentially hinting at solar influence on displacement patterns.

Conversely, the geophysical ID is almost orthogonal to the solar indicators and weather ID vectors in the biplot, which denotes a low correlation and suggests that geophysical ID follow an independent mechanism, potentially driven by stochastic geological processes or isolated external triggers.

To identify latent patterns in the joint dataset, k-means clustering was applied. The optimal number of clusters was determined using the Elbow method (Figure 7C*)* and Silhouette coefficients (Figure 7D), both of which converge on k = 3 as a meaningful and stable solution, providing well-separated clusters with practical interpretability in the context of solar activity and displacement events (Ketchen & Shook, 1996). The cluster map in PCA space (Figure 7E) demonstrates three distinguishable groups:

- Cluster 1: Periods characterized by high solar activity and elevated weather related IDs (suggesting synchronous dynamics).
- Cluster 2: Periods with low solar activity and reduced displacement.
- Cluster 3: Periods showing extremes or outliers, such as high solar activity without corresponding displacement, potentially reflecting anomalies in data reporting or nonlinear lag effects.

Notably, geophysical IDs are not consistently grouped, further reinforcing their independence from solar patterns phenomena.

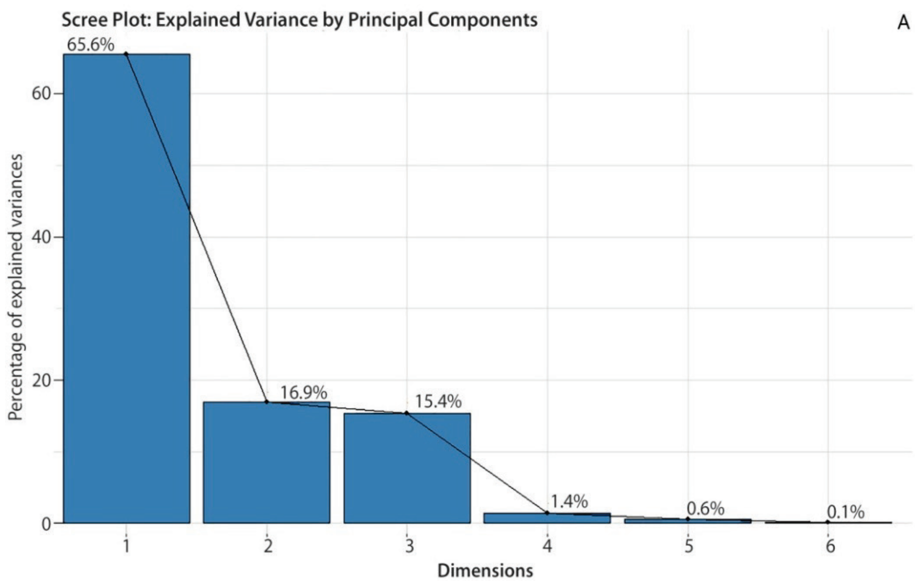

Figure 7. PCA outputs:
Panel A: Scree plot (Cattell, 1966).

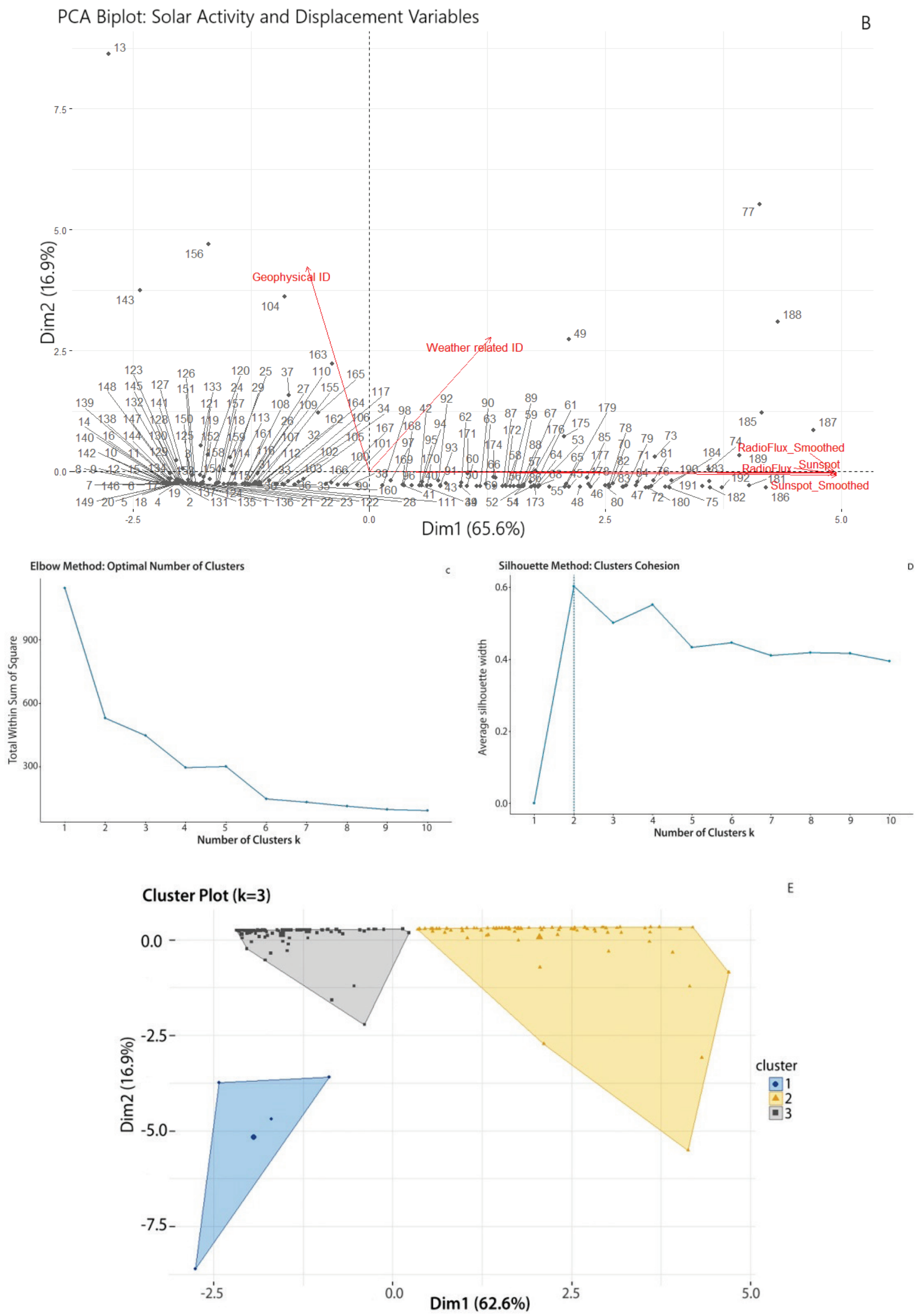

Figure 7. PCA outputs:
Panel B: PCA biplot-solar activity and displacement variables.
Panel C: Elbow method. Panel D: Silhouette method. Panel E: Cluster Plot.

5. Discussion

Natural disasters are one of the main causes of population mobility, making environmental migration and displacement a growing global trend (Black et al., 2011; MMP, 2017; Piguet et al., 2018). In Southern Europe, natural disasters affect internal displacement to varying degrees each year. It was found that in the observed period 2008–2023, the years 2014 and 2023 are characterized by the largest number of displacements. The results of this research showed that the highest intensity of internal displacement in this period is related to the years of the greatest solar activity, which particularly refer to weather related ID. Multivariate methods, such as PCA and clustering, further confirm latent patterns and the presence of structure in the data, especially in the context of weather related ID.

The results of this study, therefore, support previous research (e.g. Dmitrieva et al., 1998) that pointed to a link between solar activity and natural disasters, and go a step further by establishing a link between solar activity and population displacements induced by natural disasters. Furthermore, results in this paper are related to the findings of McConnell et al. (2021) and McConnell et al. (2024), who found that only certain extreme natural disasters have an impact on displacements and that most of them are less destructive and/or have no significant impact on population displacements. The results in this study showed the same patterns in the years with the highest solar activity (2014 and 2023). Namely, the floods in the Balkans (Bosnia and Herzegovina, Serbia, and Croatia) in May 2014 caused 88.6% of the total displacements recorded that year. In 2023, of more than 130 natural disasters that caused displacement in Southern Europe, only two of the most extreme (a storm in Italy in May and a wildfire in Greece in August) caused 41% of total internal displacement (IDMC, 2024).

As already mentioned, other trends can be observed in the context of geophysical ID. Although some research (Yanchukovsky, 2021) indicates that the number of strong earthquakes occurs during the decline phase of solar activity, no linkages were found between solar activity and geophysical ID. Such a pattern may be related to the specificity of earthquakes and their local character, as well as the possibility of being influenced by other external factors.

The research outcomes also provide an opportunity to consider the issue from the perspective of the further development of strategies and other important documents. Whereas the overall impact of natural disasters, numerous countries express concern about the impact of climate change on mobility and address this issue in various practical documents (Kraler et al., 2020). This topic is also the subject of research initiatives, such as COST Action CA22162 *FutureMed: A Transdisciplinary Network to Bridge Climate Science and Impacts on Society* (COST, n.d.). The results of this research show that the characteristics of solar activity should be considered when addressing climate change and natural disasters and their impact on population displacement. This paper therefore supports the development of evidence-based policy and suggests that the analysis of solar activity patterns has the potential to be taken into account in strategies and other key documents. In particular, the evidence that there is a greater intensity of weather related ID during periods of greater solar activity could be considered relevant for policy makers and disaster response teams to take various precautionary measures that can be implemented at different territorial levels. Accurate predictions of the impact of solar activity on the population could be important for planning and preparedness in order to minimize socio-economic impacts (Fry, 2012), as well as to inform society in appropriate time.

Although the research has yielded important results, it is necessary to point out certain limitations. They are related primarily to the fact that there are no data on displacement in longer time series (which has led the authors to limit the study to a specific period), and that there is a data limitation on internal displacements at the monthly level for the period 2008–2012. While these circumstances did not affect the core of the findings in this study, it is important to point them out so that researchers in future works could base their studies accordingly. Despite the limitations mentioned, the importance and strengths of this study should also be emphasized. The paper brings insights that have not yet been studied in the international literature and establishes a methodological framework that can be considered valuable and used as such in future interdisciplinary research. Statistical methods used in the paper provide important results that open up new thinking about the impact of solar activity on society. The paper provides an introduction to a new field of research the importance of which is reflected in its potential to contribute to societal progress. It is believed that this research field deserves the attention of the academic community and that it has great potential to develop in the future.

6. Conclusion

Although numerous studies examine the impact of solar activity on natural disasters, little is known about the indirect impact of solar activity on population displacement. This paper bridges the gap by focusing in particular on linkages between solar activity and natural disaster induced displacement.

As this topic has not been studied before, according to the authors' knowledge, this research can be considered as an introduction to a new scientific subfield. The paper therefore goes beyond the scope of previous research that studied population displacement and provides an insight into the broader context of the process, thus contributing to a better understanding of the solar-terrestrial environment. The particular importance of this research is reflected in the fact that its results have the potential to be considered in development of strategies and key documents in the field of environmental migration and displacement.

Findings on the relationship between solar activity and weather related ID provide a platform for further investigation of this issue from various aspects. Considering the different trends in internal displacements according to hazard category and solar activity indicator, it would be desirable that these two aspects are considered differently on different territorial level. Future studies should also focus on the impact of solar activity on displacement patterns in various regions to determine whether the characteristics of this process are different between them. Given the established connection between solar activity and patterns of internal displacements, future research will also focus on projections of potential patterns of internal displacements based on the progression of the solar cycle. In the future, the possible effects of solar activity on other social processes should also be investigated.

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References

Balogh, A., Hudson, H. S., Petrovay, K., & von Steiger, R. (2014). Introduction to the Solar Activity Cycle: Overview of Causes and Consequences. *Space Science Reviews, 186*(1–4), 1–15. http://dx.doi.org/10.1007/s11214-014-0125-8

Black, R., Adger, W. N., Arnell, N. W., Dercon, S., Geddes, A., & Thomas, D. S. G. (2011). The effect of environmental change on human migration. *Global Environmental Change*, *21*, 3–11. doi:10.1016/j.gloenvcha.2011.10.001

Box, G. E. P., Jenkins, G. M., Reinsel, G. C., & Ljung, G. M. (2015). *Time Series Analysis: Forecasting and Control* (5th ed.). Wiley.

Cattell, R. B. (1966). The Scree Test For The Number Of Factors. *Multivariate Behavioral Research*, *1*(2), 245–276. http://dx.doi.org/10.1207/s15327906mbr0102_10

Cleveland, R. B., Cleveland, W. S., McRae, J. E., & Terpenning, I. (1990). STL: A Seasonal-Trend Decomposition Procedure Based on Loess. *Journal of Official Statistics*, *6*(1), 3–73. https://www.wessa.net/download/stl.pdf

COST. (n.d.). *Action CA22162 — FutureMed: A transdisciplinary network to bridge climate science and impacts on society*. Retrieved from https://www.cost.eu/actions/CA22162/

Czymzik, M., Muscheler, R., & Brauer, A. (2016). Solar modulation of flood frequency in central Europe during spring and summer on interannual to multi-centennial timescales. *Climate of the Past, 12,* 799–805. https://doi.org/10.5194/cp-12-799-2016

Dmitrieva, I. V., Zaborova, E. P., & Obridko, V. N. (1998). Natural disasters and solar activity (based on chronicles and annals). *Astronomical & Astrophysical Transactions, 17*(1), 29–33. https://doi.org/10.1080/10556799808235421

Ekoh, S. S., Teron, L., Ajibade I., & Kristiansen, S. (2022). Flood risk perceptions and future migration intentions of Lagos residents. *International Journal of Disaster Risk Reduction*, *83*, Article 103399. https://doi.org/10.1016/j.ijdrr.2022.103399

EM-DAT. (2025). *EM-DAT – Country profiles* [Data set]. https://data.humdata.org/dataset/emdat-country-profiles

EMN. (2023). *Displacement and migration related to disasters, climate change and environmental degradation – EMN*. https://emn.ie/publications/climate-change-and-migration/

Fabling, R., Grimes, A., & Timar, L. (2022). Emigration and employment impacts of a disastrous earthquake: country of birth matters. *Regional Studies*, *57*(12), 2491–2502. https://doi.org/10.1080/00343404.2022.2129607

Fry, E. K. (2012). The risks and impacts of space weather: Policy recommendations and initiatives. *Space Policy*, *28*(3), 180–184. https://doi.org/10.1016/j.spacepol.2012.06.005

Gomez, J. F. P., & Radovanović, M. (2008). Solar activity as a possible cause of large forest fires—A case study: Analysis of the Portuguese forest fires. *Science of The Total Environment, 394*(1), 197–205. https://doi.org/10.1016/j.scitotenv.2008.01.040

Granger, C. W. J. (1969). Investigating causal relations by econometric models and cross-spectral methods. *Econometrica*, *37*(3), 424–438. https://doi.org/10.2307/1912791

Hathaway, D. H. (2010). The Solar Cycle. *Living Reviews in Solar Physics, 7*, Article 1. https://doi.org/10.12942/lrsp-2010-1

Hathaway, D. H. (2015). The Solar Cycle. *Living Reviews in Solar Physics*, *12*, Article 4. https://doi.org/10.1007/lrsp-2015-4

Hong-yan, L., Li-jun, X., & Xiao-jun, W. (2015). Relationship between solar activity and flood/drought disasters of the Second Songhua river basin. *Journal of Water and Climate Change*, *6*(3), 578–585. https://doi.org/10.2166/wcc.2014.053

IDMC. (2023). *Global report on internal displacement 2023: Internal displacement and food security*. https://www.internal-displacement.org/global-report/grid2023/

IDMC. (2024). *Country profiles* [Data set]. https://www.internal-displacement.org/countries/

IDMC. (2025). *Displacement data* [Data set]. https://www.internal-displacement.org/database/displacement-data/

Jolliffe, I. T. (2002). *Principal Component Analysis* (2nd ed.). Springer.

Ketchen, D. J., & Shook, C. L. (1996). The application of cluster analysis in strategic management research: An analysis and critique. *Strategic Management Journal, 17*(6), 441–458. https://doi.org/10.1002/(SICI)1097-0266(199606)17:6<441::AID-SMJ819>3.0.CO;2-G

Kraler, A., Katsiaficas, C., & Wagner, M. (2020). *Climate Change and Migration. Legal and policy challenges and responses to environmentally induced migration.* European Parliament. https://www.europarl.europa.eu/RegData/etudes/STUD/2020/655591/IPOL_STU(2020)655591_EN.pdf

Kwiatkowski, D., Phillips, P. C. B., Schmidt, P., & Shin, Y. (1992). Testing the null hypothesis of stationarity against the alternative of a unit root. *Journal of Econometrics*, *54*(1–3), 159–178. https://doi.org/10.1016/0304-4076(92)90104-Y

Langović, M., Popović, S., Dragićević, S., Stojanović, Ž., & Manić, E. (2024). Assessment of the Economic Consequences of River Bank Erosion: The Case of the South Morava River, Serbia. *Water Economics and Policy, 10*(2), Article 2450003. https://doi.org/10.1142/S2382624X24500036

Laurenz, L., Ludecke, H-J., & Luning, S. (2019). Influence of solar activity changes on European rainfall. *Journal of Atmospheric and Solar-Terrestrial Physics, 185*, 29–42. https://doi.org/10.1016/j.jastp.2019.01.012

Little, R. J. A., & Rubin, D. B. (2002). *Statistical Analysis with Missing Data* (2nd ed.). Wiley.

Lütkepohl, H. (2005). *New Introduction to Multiple Time Series Analysis*. Springer.

Malinović-Milićević, S., Radovanović, M. M., Radenković, S. D., Vyklyuk, Y., Milovanović, B., Milanović Pešić, A., Milenković, M., Popović, V., Petrović, M., Sydor, P., & Gajić, M. (2023). Application of Solar Activity Time Series in Machine Learning Predictive Modeling of Precipitation-Induced Floods. *Mathematics, 11*(4), Article 795. https://doi.org/10.3390/math11040795

Malinović-Milićević, M., Vyklyuk, Y., Radovanović, M. M., Milenković, M., Milanović Pešić, A., Milovanović, B., Popović, T., Sydor, P., & Petrović, M. D. (2024). Applying machine learning in the investigation of the link between the high-velocity streams of charged solar particles and precipitation-induced floods. *Environmental Monitoring and Assessment, 196*, Article 400. https://doi.org/10.1007/s10661-024-12537-x

Marchiori, L., Maystadt, J-F., & Schumacher, I. (2012). The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management, 63*(3), 355–374. https://doi.org/10.1016/j.jeem.2012.02.001

Mbaye, L. M., & Okara, A. (2023). *Climate change, natural disasters, and migration*. IZA World of Labor, 346v2. https://doi.org/10.15185/izawol.346v2

Mbaye, L. M., & Zimmermann, K. F. (2015). *Environmental Disasters and Migration* (IZA Discussion Papers, No. 9349). Institute for the Study of Labor (IZA). https://www.econstor.eu/bitstream/10419/124866/1/dp9349.pdf

McConnell, K., Fussell, E., DeWaard, J., Whitaker, S., Curtis, K. J., St. Denis, L., Balch, J., & Price, K. (2024). Rare and highly destructive wildfires drive human migration in the U.S. *Nature Communications, 15*, Article 6631. https://doi.org/10.1038/s41467-024-50630-4

McConnell, K., Whitaker, S., Fussell, E., DeWaard, J., Curtis, K., Price, K., St. Denis, L., & Balch, J. (2021). *Effects of Wildfire Destruction on Migration, Consumer Credit, and Financial Distress.* Working Paper No. 21–29. Federal Reserve Bank of Cleveland. https://doi.org/10.26509/frbc-wp-202129

Milenković, M., Radovanović, M., & Ducić, V. (2011). The Impact of Solar Activity on the Greatest Forest Fires of Deliblatska peščara (Serbia). *Forum geografic. Studii şi cercetări de geografie şi protecţia mediului, 10*(1), 107–116. https://doi.org/10.5775/fg.2067-4635.2011.026.i

MMP. (2017). *Migration, displacement, and the environment* (Briefing Paper 03). Mixed Migration Platform. https://mixedmigration.org/wp-content/uploads/2018/05/032_migration-displacement-environment.pdf

Montgomery, D. C., Peck, E. A., & Vining, G. G. (2021). *Introduction to Linear Regression Analysis* (6th ed.). Wiley.

Nina, A., Srećković, V. A., & Radovanović, M. (2019). Multidisciplinarity in research of extreme solar energy influences on natural disasters. *Sustainability, 11*, Article 974. https://doi.org/10.3390/su11040974

Piguet, E., Kaenzig, R., & Guélat, J. (2018). The uneven geography of research on "environmental migration". *Population and Environment*, *39*, 357–383. https://doi.org/10.1007/s11111-018-0296-4

R Core Team. (2024). *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing.

Radovanović, M. M., Pavlović, T. M., Stanojević, G. B., Milanović, M. M., Pavlović, M. A., & Radivojević, A. R. (2015). The Influence of Solar Activities on Occurrence of the Forest Fires in South Europe. *Thermal Science, 19*(2), 435–446. https://doi.org/10.2298/TSCI130930036R

Rousseeuw, P. J. (1987). Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics*, *20*, 53–65. https://doi.org/10.1016/0377-0427(87)90125-7

South American Conference on Migration. (2022). *Regional guidelines on the protection and assistance of cross-border displaced persons and migrants in countries affected by disasters.* TS-SACM, IOM, PDD, IEH. https://csmigraciones.org/sites/default/files/2022-01/CSM_Lineamientos%20Regionales_ENG.pdf

Shestopalov, I. P., & Kharin, E. P. (2014). Relationship between solar activity and global seismicity and neutrons of terrestrial origin. *Russian Journal of Earth Sciences, 14*(1), Article ES1002. https://doi.org/10.2205/2014ES000536

Shumway, R. H., & Stoffer, D. S. (2017). *Time Series Analysis and Its Applications: With R Examples* (4th ed.). Springer.

Sida. (2024). *Migration, Forced Displacement and Climate Change*. Thematic Support Unit, Swedish International Development Cooperation Agency. https://www.sida.se/en/about-sida/publications/migration-forced-displacement-and-climate-change

Singh, A., & Patel, K. (2021). Statistical Study of Solar Activity Parameters of Solar Cycle 24. *Journal of Scientific Research, 65*(1), 197–200. https://doi.org/10.37398/JSR.2021.650125

Srećković, V. A. (2023). New Challenges in Exploring Solar Radiation: Influence, Consequences, Diagnostics, Prediction. *Applied Sciences, 13*(7). Article 4126. https://doi.org/10.3390/app13074126

Srećković, V. A., Kolarski, A., Langović, M., Arnaut, F., Jevremović, S., & Mijić, Z. R. (2025). The strongest solar flares of Solar Cycle 25 and their subionospheric impact: data and modeling. *Contributions of the Astronomical Observatory Skalnaté Pleso, 55(*2), 88–94. https://doi.org/10.31577/caosp.2025.55.2.88

Stojanov, R. (2021). *Climate migration Case Study.* Diaconia ECCB Center of Relief and Development.

SWL (SpaceWeatherLive.com). (2025). *Solar Cycle progression.* Available from https://www.spaceweatherlive.com/en/solar-activity/solar-cycle.html

Tentomas, G., & Marsellos, A. E. (2022). Sunspot Number Effects on Earth's Climate Change and Water Sustainability for Long Island, NY. *29th Conference on the Geology of Long Island and Metropolitan New York*. https://www.stonybrook.edu/commcms/geosciences/about/_LIG-Past-Conference-abstract-pdfs/2022-Abstracts/Tentomas.pdf

Tsuda, T., Shepherd, M., & Gopalswamy, N. (2015). Advancing the understanding of the Sun–Earth interaction—the Climate and Weather of the Sun–Earth System (CAWSES) II program. *Progress in Earth and Planetary Science, 2*, Article 28. https://doi.org/10.1186/s40645-015-0059-0

UNFPA. (2024). *Disaster displacements disproportionately impact women, girls in fragile contexts.* United Nations Population Fund. https://www.unfpa.org/sites/default/files/resource-pdf/Disaster%20displacements%20UNFPA-IDMC%20FactSheet_v03.pdf

Whitehouse, D. (2020). *The next solar cycle and why it matters for climate*. The Global Warming Policy Foundation. https://www.thegwpf.org/content/uploads/2020/04/SolarCycle25.pdf

Xiao, Z., Zhao, L., Zhou, L., Huo, W., Mironova, I., & Miyahara, H. (2024). Editorial: Impact of solar activities on weather and climate. *Frontiers in Earth Science, 11.* Article 1338416. https://doi.org/10.3389/feart.2023.1338416

Yanchukovsky, V. L. (2021). Solar activity and earth seismicity. *Solar-Terrestrial Physics, 7*(1), 67–77. https://doi.org/10.12737/stp-71202109